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Effects of Low Application Rates of Digested Sewage Sludge on Yield and Elemental Uptake of Corn, Soybeans, and Wheat

TERRY J. LOGAN

ROBERT H. MILLER

The Ohio State University
Ohio Agricultural Research and Development Center
Wooster, Ohio

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Effects of Low Application Rates of Digested Sewage Sludge on Yield and Elemental Uptake of Corn, Soybeans, and Wheat[1]

TERRY J. LOGAN and ROBERT H. MILLER[2]

INTRODUCTION

In 1978 the Departments of Agronomy, Agricultural Economics and Rural Sociology and Agricultural Engineering at The Ohio State University and the Ohio Agricultural Research and Development Center, the Cooperative Extension Service, and the Departments of Veterinary Preventive Medicine and Medical Microbiology, The Ohio State University, entered into a cooperative agreement with the Ohio Farm Bureau Federation and the USEPA Municipal Environmental Laboratory to conduct a demonstration research project on utilization of municipal sewage sludge on Ohio farmland.

The study, completed in 1982, had two major components: a) research on the exposure of livestock and farm families to pathogens and parasites in sludge applied to farmland, and b) the agronomic effectiveness and environmental effects (primarily trace metal accumulation by crops) of land application of municipal sludges. This bulletin presents data from the 5-year field experiment with Columbus sludge at The Ohio State University Farm Science Review, Columbus.

METHODS AND MATERIALS

Centrifuged Columbus Jackson Pike anaerobically digested sewage sludge was used for the study. The required quantity was hauled to the site and stockpiled no more than 2 days prior to spreading. A small front-end loader was used to transfer sludge to a commercial side-throw flail manure spreader. The rate of application was measured by running the spreader at a designated speed and rpm and then collecting and weighing sludge on sheets of paper 45 cm x 45 cm. This gave a rate of 6.5 mt/ha dry sludge in 1978, 1979, 1981, and 1982 and 5.5 mt/ha in 1980. A double rate was also applied (11 and 13 mt/ha) each year by spreading on the same plot twice.

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[1]Supported in part by the Ohio Farm Bureau Federation-U. S. Environmental Protection Agency (EPA) Cooperative Agreement No. CS805189. The contents of this report do not necessarily reflect the views and policies of the EPA, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

[2]Professor, Dept. of Agronomy, and former Professor, Dept. of Agronomy. Dr. Miller is currently Head, Soil Science Department, North Carolina State University, Raleigh.

The sludge was incorporated by moldboard plowing and disking within 24 hours of spreading and the crop was planted within 2 days after disking. In the fall of 1978, sludge was applied at the half rate prior to planting wheat but no sludge was applied to the full rate plots for wheat. The sludge treatments were repeated on the plots and agricultural lime was added in the fall of 1978 (after the first crop) to raise soil pH to 6.5. Because of variability in soil pH among the plots and the small difference between unlimed and limed pH ($\sim$6.0 vs 6.5), this treatment gave no differences between any of the dependent variables studied. These additional sludge plots were therefore treated as replicates of the sludge treatments.

All treatments were replicated twice, with one replicate cropped with corn each year and the other in a corn-wheat-corn-soybean-corn rotation. In addition, all treatment combinations were replicated in three blocks, with treatments randomized within each block. Each plot was 9.1 m wide and 30.5 m long except the fertilizer and control plots, each of which was 9.1 m wide and 15.25 m long and placed next to each other to give the same dimension as the other plots. A 10.7 m buffer area was left between each block as a turn path for the spreader.

The fertilizer treatment for corn was 220 kg N/ha as NH_4NO_3 and 40 kg P/ha as monocalcium phosphate, applied by hand just before plowing. A blanket application of 65-200 kg K/ha was applied to the entire experiment each spring (depending on the potassium soil test) so as to eliminate potassium as a variable in the study. About 40 kg P/ha was applied in the spring to the fertilizer plots prior to planting soybeans but no nitrogen was added. About 50 kg N/ha and 50 kg P/ha were added to the fertilizer plots just prior to planting wheat.

Soil samples were taken from each plot in the spring of 1978 before the start of the experiment, and thereafter in the fall after crop harvest. The soils were analyzed for: pH; Bray Pl available P; DTPA extractable and total Cd, Cu, Ni, Pb, and Zn. Plant leaves were sampled at tasseling (corn), flower initiation (soybeans), or heading (wheat), and analyzed for Cd, Cu, Ni, Pb, and Zn. Crop yields were measured by hand harvesting 15 m of row. Grain was analyzed for Cd, Cu, Ni, Pb, and Zn.

Methods of Sludge Analysis

pH

Determined directly in liquid sludges. Cake sludge is made into a slurry with distilled water before measurement.

Total Kjeldahl Nitrogen

The microKjeldahl procedure of Bremner (1) was used. A 5 ml aliquot of liquid sludge was pipetted directly into the Kjeldahl flask. The procedure then followed Bremner (1). N was determined by steam distillation.

Total Metals and Potassium

The liquid sludges were freeze-dried prior to analysis of metals, phosphorus, and potassium. A 0.5 g sample was placed in a pyrex test tube (calibrated to 50 ml volume) on a machined aluminum block which was heated by a Linberg "Heavy-Duty" hot plate. Five to ten ml of concentrated HNO_3 was added and small glass funnels were placed in the mouths of the tubes for refluxing. The mixture was slowly brought to 200° C and the volume reduced to about 5 ml. Three ml of concentrated perchloric acid was then added and the mixture digested for 75 minutes. The samples were cooled and the tubes made to volume with double distilled deionized water. They were thoroughly shaken and allowed to stand for 24 hours. For total metals, the supernatant was used directly for analysis by atomic absorption spectroscopy using a Varian Model 375 with background correction and an HP9815A calculator for curve fitting. Metals analyzed included Cd, Cu, Cr, Pb, Ni, and Zn. For potassium, 4 ml of the diluted digest was further diluted to 50 ml and potassium was determined by flame emission on the AA.

Phosphorus

A 1-ml aliquot of the diluted digest used for potassium analysis was transferred to a 100-ml volumetric flask. Two drops of 25% 2,4-dinitrophenol were added and then 0.5*N* NaOH until the color just turned to pale yellow. Ten ml of Murphy-Riley solution, as described by Knudsen (3), containing 1.5 g L-ascorbic acid/100 ml was added to the volumetric flask and the mixture was diluted to volume with distilled water. After 30 minutes, the absorbance was read on a Beckman Model 24 UV-visible spectrophotometer at 730 nm.

Solids

A sample of sludge containing 50-75 g wet solids was transferred to a beaker, weighed on an analytical balance, oven-dried at 80° C for 48 hours, and reweighed.

Methods of Soil Analysis

pH

1:1 in water.

Bray P1 Available P

Knudsen (3). Absorbance measured at 730 nm. Detection limit 1.0 μg P/g soil.

Total Kjeldahl Nitrogen

Bremner (1). Digestion with concentrated H_2SO_4 and catalyst ($K_2SO_4/CuSO_4/Se$) on Labconco microKjeldahl digestion apparatus. Neutralized with 10N NaOH and steam distilled into boric acid. Titrated with 0.01N HCl. Detection limit 100 μg N/g soil.

Total Metals

A 2 g sample of soil was placed in a 100-ml pyrex glass tube in a machined aluminum block on a hot plate in a perchloric acid hood. Five ml of concentrated perchloric acid was added, the tube covered with a small glass funnel for refluxing, and the sample digested for 75 minutes at 200° C. After cooling, the sample was filtered with No. 1 filter paper, brought to 50 ml in a precalibrated test tube, mixed, and metals analyzed by atomic absorption spectroscopy. The six metals (Cd, Cu, Cr, Ni, Pb, Zn) were all analyzed on a Varian Model 375 spectrophotometer with an air-acetylene flame and background correction. Detection limits for the metals were Cd — 0.25; Ni — 1.25; Pb — 4.0; Cu — 2.0; Cr — 2.0; Zn — 3.0 μg/g soil.

Total Phosphorus

An aliquot of the filtered perchloric acid digest for total metals which was diluted to 50 ml was further diluted 50-100 fold as needed and P was analyzed as ascorbic acid reduced phosphomolybdate at 730 nm. Detection limit 25 μg P/g soil.

Total Potassium

An aliquot of the filtered perchloric acid digest for total metals which was diluted to 50 ml was further diluted 25 fold and K was determined by flame emission on the Varian Model 375 spectrophotometer. Detection limit 200 μg K/g soil.

DTPA Extractable Metals

Soils were extracted with 0.005M DTPA (diethylenetriaminepenta-acetic acid), 0.1M triethanolamine and 0.01M $CaCl_2$ at pH 7.3 according to Lindsay and Norvell (4). The extracted metals were analyzed as for total metals. Detection limits were Cd — 0.02; Ni — 0.10; Pb — 0.32; Cu — 0.16; Cr — 0.16; Zn — 0.24 μg/g soil.

Methods of Plant Analysis

Total Kjeldahl Nitrogen

A 0.2-g sample of ground plant material was digested and analyzed as was described for sludge.

Total Metals

Five grams of ground plant materials were weighed into 250 ml Erlenmeyer flasks. Twenty to thirty ml of concentrated HNO_3 was added and the mixture was allowed to sit at room temperature in a fume hood for at least 1 hour. Samples were heated to just evaporate the nitric acid over a 2-hour period. The samples were kept at low temperature for 8-24 hours until they were lemon colored and then were cooled and filtered into 20 ml volume calibrated test tubes. Metals were determined directly on the digests by flame AA.

Phosphorus and Potassium

A 0.5-g sample was digested as described for total metals and the digest was then diluted to 100 ml. Further dilutions were made as necessary to get the concentration into the desired range. Phosphorus was determined by ascorbic acid-reduced phosphomolybdate as described for sludge analysis. Potassium was analyzed by flame emission on the AA.

RESULTS AND DISCUSSION

Sludge Analysis

The analyses of Columbus sludge used each year are given in Table 1. These were used to calculate the annual additions of N, P, K, and Cd, and the cumulative addition of Cd, Cu, Ni, Pb, and Zn (Table 2). The nitrogen supplied by the half rate of sludge was probably low for corn, as was the full rate in 1979. However, this soil (Crosby silt loam with some Kokomo loam) has a fairly high organic matter content (3-5%) and N mineralization from the soil is probably substantial. Phosphorus supplied by sludge was high at all rates, but potassium supply was only half of what a corn crop would normally require on this soil. However, potash was applied uniformly to the experiment area each year, so potassium supply would not be limiting. Annual Cd application rate was below the 2.0 kg/ha/yr allowed by EPA (6) in all years, although the 1.86 kg/ha applied in 1979 approached this value. Cumulative amounts of the five metals studied were well within the levels allowed by Ohio EPA (5) for a soil with a CEC between 5 and 15 meq/100 g.

Yields

Crop yields are given in Table 3. There was a response of corn to fertilizer or sludge in all years except the first. The area used for this

TABLE 1.—Analysis of the Columbus Jackson Pike Anaerobically Digested Sewage Sludge Used in the Study (1978-1982).

	pH	Solids Percent	NH_3-N	Organic N	Available N‡	P	K	Cd	Cu	Ni	Pb	Zn	Cr
			kg/mt Dry Sludge										
1978	7.3	*	6.0†	29.2	14.8	27.5	4.9	0.059	0.71	0.33	0.63	5.10	
1979	7.3	*	6.0	19.3	11.8	26 8	4 2	0.143	0 80	0.29	0.30	5.66	0.63
1980	7.8	19.7	6.4	32.9	15.6	25.2	4.1	0 061	0.73	0.51	0 87	5.63	0.99
1981	8.1	16.8	7.9	42.8	20.0	25.1	4.1	0.095	0.72	0.33	0.61	4.62	0.59
1982	7.6	19.5	4.4	29.8	12.9	25.5	4.4	0.061	0.69	0.23	0.48	3.27	0.51

*The solids on the centrifuged sludge were not analyzed in this period.
†Estimated from the mean of monthly analyses for 1978-1982.
‡Assumes 30% of the organic N is available and that 10% of the NH_3-N is lost by volatilization.

TABLE 2.—Annual Rates of Application of N, P, K, and CD, and Cumulative Applications of Cd, Cu, Ni, Pb, and Zn (1978-1982).

Year	Sludge Rate (mt/ha)	Annual Loading (kg/ha/yr)				Cumulative Loading (kg/ha)				
		Available N*	P	K	Cd	Cd	Cu	Ni	Pb	Zn
1978	6.5	96	179	32	0.38	0.38	4.6	2.1	4.1	33.2
	13.0	192	358	64	0.76	0.76	9.2	4.2	8.2	66.4
1979	6.5	77	174	27	0.93	1.31	9.8	4.0	6.1	70.0
	13.0	154	348	54	1.86	2 62	19.6	9.0	12.2	140 0
1980	5.5	86	139	23	0.34	1.65	13.8	6.8	10.9	101.0
	11.0	172	278	46	0.68	3.30	27.6	13.6	21.8	202.0
1981	6.5	130	163	27	0.62	2.27	18.5	8.9	14.9	131.0
	13.0	260	326	54	1.24	4.54	37.0	17.8	29.8	262.0
1982	6.5	84	166	29	0.40	2.67	23.0	10.4	18.0	152.3
	13.0	168	332	58	0.80	5.34	46.0	20.8	36.0	304.6

*Assumes 30% of the organic N is available and that 10% of the NH_3-N is lost by volatilization.

TABLE 3.—Crop Yields on the Sludge Plots (1978-1982).

Treatment	Corn 1978	Corn 1979	Corn 1980	Corn 1981	Corn 1982	Wheat§ 1979	Soybeans 1981
	kg/ha						
Control	9,030 b*	4,700 b	7,090 c	3,510 c	6,020 b	1950 b	2820 a
Fertilizer†	10,040 ab	7,840 a	9,720 a	6,840 a	8,090 a	2020 b	2820 a
Full Rate‡	9,720 ab	7,840 a	9,910 a	6,520 a	6,960 ab	3900 a	2690 a
Half Rate	10,410 a	7,650 a	8,470 b	5,580 b	5,710 b	3230 a	2690 a

§Wheat was rotated after corn and only the half rate was applied before planting wheat.
*Means within the same vertical columns followed by the same letter are not different from each other ($p = 0.05$)
†Soil test recommended rate No nitrogen was applied to soybeans or wheat
‡Full rate was 13 mt/ha in 1978, 1979, 1981, and 1982, and 11 mt/ha in 1980. Potassium at recommended rate applied to all sludge plots.

experiment had been used for corn previously, and there may have been carryover of residual nitrogen which affected corn response to sludge or fertilizer N in 1978. This is suggested by the high check plot yield (9,030 kg/ha) in that year compared to 3500-7000 kg/ha in following years. There were no differences between the fertilizer and full-rate sludge treatments, while the half rate of sludge tended to be lower than the full rate or the fertilizer treatments except in 1978.

There was a significant response of wheat to both rates of sludge addition. This was a nitrogen response, and the fertilizer treatment did not give higher yields because the wheat on this treatment matured more rapidly and lodged before it could be harvested. There was also some shattering of seed heads before and during harvesting which contributed to yield loss. There was slower maturity and no lodging on the sludge plots.

There were no yield differences on the soybean plots. This was expected since soybeans fix their own nitrogen and phosphorus soil tests were high enough to preclude a response to P.

Leaf and Grain Analysis

The nutrient (N, P, K) and metal contents of corn leaves and grain are given in Table 4. Different hybrids were used each year, so comparisons should not be made from 1 year's results to another. However, the effect of repeated sludge applications can be made by comparing the change in the elemental composition of corn tissue from the sludge-treated plots with concentrations from the control and fertilizer plots.

Nitrogen in the leaf was only evaluated in 1978, and results show that the half rate of sludge had significantly lower N concentration than the fertilizer treatment, while the full rate was the same as the fertilizer treatment. Table 2 indicates that the half rate in 1978 only supplied 96 kg N/ha, about half the normal N needs of corn. There were no treatment differences in grain N in 1978 and 1979, but grain N was significantly lower on the sludge treatments than the fertilizer treatment in 1981.

There were differences in leaf P only in 1978 and 1982, where leaf P on the control plots was lower than the fertilizer or sludge treatments. Grain P generally showed few consistent differences among treatments. The lack of response of tissue P to the treatments is not unexpected since the Bray P1 soil test levels were above the sufficiency level of 15-20 μg P/g on all plots (Table 5). There were also no differences in leaf K and no consistent differences in grain K. Potassium was applied uniformly to all plots and there were no differences in exchangeable K in any year (Table 5).

TABLE 4.—Leaf and Grain Contents of Nutrients and Heavy Metals in Corn Grown with Columbus Sewage Sludge at Farm Science Review.

	Leaf							
Treatment	N	P	K	Cd	Cu	Ni	Pb	Zn
	$\mu g/g$							
	1978							
Control	28800b†	2580b	2250a	1 08b	8.5b	0.1b	1.4a	32.3c
Fertilizer	31900a	2790a	2340a	1.82ab	10.0a	0.2ab	1.6a	42.2b
Sludge-Half Rate*	29400b	2800a	2570a	1.93a	9.3ab	0.2a	1.6a	47.7ab
Sludge-Full Rate*	30400ab	2700a	2380a	2.08a	9.2b	0.2ab	1.5a	49.9a
	1979							
Control								
Fertilizer								
Sludge-Half Rate								
Sludge-Full Rate								
	1980							
Control		3070a	23200a	0.16b	7.6b	0.1a	8.3a	31.2c
Fertilizer		2990a	25800a	0.20ab	8.9a	0.1a	5.3b	38.8bc
Sludge-Half Rate		3110a	23400a	0.24ab	8.0b	<0.1a	4.9b	50.3ab
Sludge-Full Rate		3090a	24900a	0 28a	8.1b	<0.1a	5.5b	61.2a
	1981							
Control		3090a	20500a	0.11ab	5.7b	0.8a	1.8a	28.7c
Fertilizer		2820a	21800a	0.10b	7.4a	1.2a	1.7a	35.1bc
Sludge-Half Rate		2830a	21900a	0.11ab	6.3ab	0.4a	1.5a	41.0ab
Sludge-Full Rate		2760a	20300a	0.14a	6.9ab	1.2a	1.3a	48.8a
	1982							
Control		1480b	21500a	0.30b	3.6bc	0.3a		28.8b
Fertilizer		2270a	22100a	0.36a	5.1a	0.2a		38.3a
Sludge-Half Rate		1990a	21000a	0.31b	3.2c	0.2a		30.3b
Sludge-Full Rate		2160a	21000a	0.35a	3.9b	0.3a		38.9a

*Half rate = 6.5 mt/ha (5.5 mt/ha in 1980); full rate = 13 mt/ha (11 mt/ha in 1980).
†Means within the vertical columns followed by the same letter are not different from each other ($p = 0.05$).

TABLE 4 (Continued).—Leaf and Grain Contents of Nutrients and Heavy Metals in Corn Grown with Columbus Sewage Sludge at Farm Science Review.

Treatment	Grain							
	N	P	K	Cd	Cu	Ni	Pb	Zn
	μg/g							
				1978				
Control	11400a†	2020a	2120b	0.14c	2.1a	0.8a		15.7c
Fertilizer	12100a	2160a	2580 a	0.16bc	2.1a	0.5a		16.8bc
Sludge-Half Rate*	11900a	2150a	2300ab	0.19b	2.1a	0.4a		18.2ab
Sludge-Full Rate*	12200a	2210a	2330ab	0.25a	3.0a	0.7a		19.7a
				1979				
Control	13000a	2680a	3310a	0.17a	1.8a	1.0a		18.4b
Fertilizer	14000a	2750a	3090ab	0.15a	2.1a	1.0a		19.5ab
Sludge-Half Rate	13900a	2390ab	3070b	0.16a	2.0a	0.9a		20.6ab
Sludge-Full Rate	13700a	2110b	2950b	0.17a	2.2a	1.0a		21.5a
				1980				
Control		2850b	3450a	0.02a	0.9c	0.2a	0.1a	15.8a
Fertilizer		2530b	3100b	0.04a	1.3a	<0.1a	0.1a	16.2a
Sludge-Half Rate		2720ab	3330ab	0.04a	1.1b	0.1a	0.1a	16.5a
Sludge-Full Rate		2710ab	3210ab	0.03a	1.2ab	<0.1a	0.1a	17.5a
				1981				
Control	10300c	2410a	3160ab	0.05a	1.2b	0.2ab		15.3ab
Fertilizer	12700a	2300a	2950b	0.03a	1.3b	0.1b		11.8b
Sludge-Half Rate	11000bc	2590a	3040ab	0.02a	1.4ab	0.3a		16.7a
Sludge-Full Rate	11300b	2710a	3210a	0.04a	1.5a	0.4a		16.6a
				1982				
Control				0.09a	0.6b	0.7a	0.8a	12.8a
Fertilizer				0.10a	0.9ab	0.6a	0.8a	13.7a
Sludge-Half Rate				0.11a	0.9a	0.7a	1.0a	14.3a
Sludge-Full Rate				0.10a	0.9a	0.7a	1.0a	15.0a

*Half rate = 6.5 mt/ha (5.5 mt/ha in 1980); full rate = 13 mt/ha (11 mt/ha in 1980).
†Means within the vertical columns followed by the same letter are not different from each other ($p = 0.05$).

TABLE 5.—Soil pH and Nutrient and Metal Contents of Soil by Year After Treatment with Columbus Sewage Sludge at Farm Science Review.

Treatment	pH	Exchangeable K	Bray PI	Total N	Total P	Total K
			μg/g			
			1978			
Control	5.7a†		33.8c	1708b	638a	5800a
Fertilizer	5.2b		39.0bc	2220a	786a	6377a
Sludge-Half Rate*	5.5ab		50.6ab	1718b	665a	5481a
Sludge-Full Rate*	5.5ab		55.9a	1661b	705a	5293a
			1979			
Control	6.0a	155a	26.7b	1788a	632a	5712ab
Fertilizer	5.9a	167a	28.4b	1978a	692a	6109a
Sludge-Half Rate	5.8a	153a	41.7ab	1703a	640a	5040b
Sludge-Full Rate	6.0a	152a	54.0a	1657a	660a	5057b
			1980			
Control	6.3ab	175a	26.2c			
Fertilizer	5.9b	187a	30.8c			
Sludge-Half Rate	6.5a	179a	56.9b			
Sludge-Full Rate	6.5a	176a	79.1a			
			1981			
Control	6.2a	174a	27.9b			
Fertilizer	6.2a	168a	35.8b			
Sludge-Half Rate	6.5a	173a	89.0a			
Sludge-Full Rate	6.5a	171a	85.5a			
			1982			
Control	6.2a	260a	32.6c			
Fertilizer	4.8b	240a	34.2c			
Sludge-Half Rate	6.3a	225a	54.3b			
Sludge-Full Rate	6.4a	237a	89.9a			

*Half rate = 6.5 mt/ha (5.5 mt/ha in 1980); full rate = 13 mt/ha (11 mt/ha in 1980).
†Means within the vertical columns followed by the same letter are not different from each other ($p = 0.05$).

TABLE 5 (Continued).—Soil pH and Nutrient and Metal Contents of Soil by Year After Treatment with Columbus Sewage Sludge at Farm Science Review.

Treatment	Total					DTPA Exractable				
	Cu	Cd	Pb	Ni	Zn	Cu	Cd	Pb	Ni	Zn
	μg/g									
1978										
Control	17.5a	0.40b	32.2a	24.1a	82.2a	2.5b	0.16b	3.1b	1.3b	4.2c
Fertilizer	20.9a	0.56a	33.0a	22.3a	95.4a	3.6a	0.23a	3.6a	2.6a	5.3bc
Sludge-Half Rate*	18.8a	0.44b	34.6a	22.6a	89.7a	2.7b	0.18ab	3.2b	1.3b	6.0ab
Sludge-Full Rate*	17.6a	0.44b	32.9a	20.8a	86.7a	2.7b	0.19ab	3.4ab	1.3b	7.4a
1979										
Control	20.5a	0.27a	16.1a	20.5a	91.0a	2.1a	0.16a	1.8a	2.2a	4.5ab
Fertilizer	20.4a	0.25a	16.4a	21.4a	86.0a	2.3a	0.16a	1.9a	2.3a	2.9b
Sludge-Half Rate	20.6a	0.38a	17.3a	19.5a	92.8a	2.5a	0.21a	2.1a	1.9a	6.8a
Sludge-Full Rate	20.5a	0.41a	17.5a	18.8a	92.8a	2.4a	0.22a	2.0a	1.8a	8.1a
1980										
Control						2.9a	0.21b	2.7b	1.9a	5.6c
Fertilizer						3.3a	0.22b	3.0b	2.2a	6.1c
Sludge-Half Rate						4.3a	0.33b	3.1ab	1.8a	10.4b
Sludge-Full Rate						4.3a	0.43a	3.5a	2.3a	15.7a
1981										
Control						2.9b	0.25b	2.7b	1.7a	4.4b
Fertilizer						3.5ab	0.26b	2.7b	1.7a	4.1b
Sludge-Half Rate						4.5a	0.48a	3.1ab	1.6a	14.2a
Sludge-Full Rate						4.6a	0.54a	3.3a	1.5a	13.1a
1982										
Control	15.1a	0.85bc	2.8a	16.2a	68.3b	2.6b	0.27b	2.8b	1.9a	5.8bc
Fertilizer	15.2a	0.81c	2.8a	16.4a	63.8b	2.8b	0.24b	2.8b	2.3a	3.4c
Sludge-Half Rate	16.7a	1.02ab	3.0a	16.0a	80.4a	3.2b	0.39b	3.0ab	1.6a	9.6b
Sludge-Full Rate	17.2a	1.15a	3.3a	15.*a	86.8a	3.9a	0.55a	3.4a	1.8a	14.4a

*Half rate = 6.5 mt/ha (5.5 mt/ha in 1980); full rate = 13 mt/ha (11 mt/ha in 1980).
†Means within the vertical columns followed by the same letter are not different from each other ($p = 0.05$).

TABLE 6.—Leaf and Grain Contents of Nutrient and Heavy Metals in Wheat and Soybeans Grown with Columbus Sewage Sludge at Farm Science Review.

Treatment	Leaf							
	N	P	K	Cd	Cu	Ni	Pb	Zn
	μg/g							
	Wheat (1979)							
Control	24600b†	2470a		0.35a	32.2a	6.9a	5.7a	24.9a
Fertilizer	32000a	2570a		0.31a	27.3a	6.0a	7.2a	26.2a
Sludge-Half Rate*	24400b	2960a		0.37a	31.9a	3.3a	8.2a	27.2a
Sludge-Full Rate*	27000ab	3020a		0.35a	22.6a	2.8a	6.3a	25.1a
	Soybeans (1981)							
Control		3860a	28000a	0.59a	9.3a	3.7a	1.6ab	38.5a
Fertilizer		4050a	27000a	0.21a	7.7b	5.0a	1.7a	35.2a
Sludge-Half Rate		4240a	27000a	0.85a	9.1ab	3.4a	1.4ab	38.4a
Sludge-Full Rate		4210a	27000a	1.43a	8.1ab	3.5a	1.2b	45.4a

Treatment	Grain							
	N	P	K	Cd	Cu	Ni	Pb	Zn
	μg/g							
	Wheat (1979)							
Control	18600b	2040a	4010a	0.17a	18.0a	3.0a	6.5a	43.1a
Fertilizer	22600a	1510a	4000a	0.16a	15.8a	2.3a	6.7a	50.4a
Sludge-Half Rate	19300b	1860a	3760a	0.24a	11.0b	2.2a	5.6a	45.2a
Sludge-Full Rate	19200b	1780a	3860a	0.25a	9.8b	2.5a	6.1a	44.7a
	Soybeans (1981)							
Control	59300a	4700b	19900a	0.13a	9.1a	3.2ab	0.0a	43.0ab
Fertilizer	62700a	4680b	20400a	0.13a	5.7a	4.7a	0.0a	42.7ab
Sludge-Half Rate	60300a	5320a	21000a	0.08a	8.6a	2.6b	0.0a	40.6b
Sludge-Full Rate	60300a	5220ab	21000a	0.15a	8.7a	3.2ab	0.2a	50.9a

*Half rate = 6.5 mt/ha; full rate = 13 mt/ha.

†Means within the vertical columns followed by the same letter are not different from each other ($p = 0.05$).

Of the metals, there were consistent increases in leaf Zn and Cd with sludge application compared to the control and fertilizer plots, with the greatest Cd effects in 1978 where the corn hybrid used had much higher Cd uptake than hybrids used in subsequent years. Hinesly, *et al.* (2) have shown large differences in Cd uptake among genetic corn lines. Grain Cd and Zn from sludge-treated plots were also higher in 1978 than grain from the control or fertilizer plots. There was a trend in all years for leaf Cu from the fertilizer plots to be higher than the sludge-treated or control plots. A possible explanation for this is that Cu may have been added with fertilizer and increased leaf Cu, while Cu added with sludge may have been less bioavailable because of its strong binding with sludge organic matter.

Levels of all metals in corn leaves or grain were low for all treatments compared to concentrations which are found for corn grown in highly metal-contaminated soils.

Leaf and grain N concentrations were low in wheat grown on sludge-treated plots compared to the fertilizer treatment, and were not significantly different from those from the control plots (Table 6). The half-rate sludge treatment provided 77 kg N/ha of available N, while the full-rate treatment only provided residual N from sludge supplied to the previous corn crop (Table 2). However, wheat yields were higher from the sludge plots than from the control or fertilizer plots (Table 3). As previously explained, wheat yields from the fertilizer plots would probably have been higher, but this treatment caused considerable lodging and seed head shattering because of earlier maturity. Therefore, it is possible that wheat on the sludge plots was N-limited.

There were no differences in wheat leaf or grain metal contents except grain Cu, which was lower with the sludge treatments than the control or fertilizer treatments.

There were no consistent effects of sludge application on nutrient or metal concentrations of soybean leaves or grain (Table 6).

Soil Analysis

Soil pH; exchangeable K; Bray Pl available P; total N, P, and K; and total and DTPA-extractable metals in soil each year are given in Table 5 for the control, fertilizer, and sludge treatments.

There was a trend for higher soil pH on the sludge-treated plots. This was due to the addition of lime to half of the sludge plots in 1978. Even though liming did not significantly increase pH, and these plots were treated the same statistically, they did raise the mean pH for the sludge plots compared to the control and fertilizer treatments. Also, digested sewage sludges have a tendency to raise pH values of acid soils.

There was a consistent significant increase in Bray P1 phosphorus with sludge and fertilizer treatments. By 1980, sludge additions had raised available P levels above that for the fertilizer treatment, and the full rate of sludge had higher levels than the half rate in 1980 and 1982.

Total nutrients (N, P, K) in soil (measured only in 1978 and 1979) were generally unaffected by fertilizer or sludge additions. This is not unexpected since this fertile till soil has high background levels of these three elements. Increases in total metals in soil with sludge treatment were not noted until 1982 and only with Cd and Zn. This points out the difficulty in using soil analysis to monitor metal accumulations when low rates of sludge-borne metals are applied. DTPA-extractable metals except Ni increased with the full rate of sludge application after 1980, although there was a consistent increase in DTPA-Zn from the first year of sludge application. DTPA did not appear to be sensitive to Ni additions.

SUMMARY

Sewage sludge applied at annual agronomic rates of 11-13 mt/ha resulted in measurable increases in available phosphorus, total Cd and Zn, and DTPA extractable Cu, Cd and Zn. Rates of 5.5-6.5 mt/ha showed smaller, and in some cases nonsignificant, increases in total and extractable metals.

Sludge at 5.5-13 mt/ha/yr generally increased corn yields to the same extent as fertilizer and gave wheat yields which were superior to those with fertilizer, while sludge had no effect on soybean yields.

Uptake of metals by corn varied considerably with variety, but grain Cd was only increased significantly by the 13 mt/ha sludge rate in 1 out of 5 years. Grain Zn was increased significantly by sludge application in 1978 and 1979, the years when corn varieties with the greatest metal uptake were grown. Other metals were not increased in corn grain with sludge addition.

There was no significant uptake of metals by soybeans and only Cu was increased in wheat grain with sludge addition.

The results of this study show that municipal sewage sludge at rates of 13 mt/ha or less is a good source of nitrogen and phosphorus, gives crop yields similar to those obtained with fertilizer, and shows little accumulation of trace metals in edible grain. The trace metal contents of the Columbus sludge used in this study are above the median values found for U. S. municipal sludges. Metal uptake at the same sludge application rates should be lower with sludges lower in trace metals.

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